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THE USE OF PLANTS ACCUMULATING HEAVY METALS FOR DETOXICATION OF CHEMICALLY POLLUTED SOILS

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ABSTRACT

The studies conducted from 1997 to 1999 in a vegetation hall were performed as a pot experiment on ordinary silt with cation exchange capacity (CEC) of 81.1 cmol (+) · kg^{-1}, pH_{KCl} = 6.0 and organic C content of 9.5% serving as soil. Jerusalem artichoke, maize, *Sida hermaphrodita Rusby*, amaranth and hemp were used as indicator plants. The results confirmed, implied earlier, great diversification of the element contents which depends not only on the species but also on the part of plants. Analysis of the data revealed also another dependence: increased concentration of heavy metals in the soil corresponds to higher content of heavy metals in the plants. Significant differences were observed for the plant species from unpolluted and contaminated at various levels treatments.

Key words: detoxication, heavy metals, plants, polluted soils

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INTRODUCTION

Industrial activities cause fast and considerable degradation of soil and vegetation cover, which necessitates pursuing the methods of managing derelict industrial lands. On such chemically devastated lands vegetation plays increasingly important ecological and sanitary role. Proper management of plants from such areas may significantly contribute to restoring the natural environment[18]. Numerous efforts have been undertaken recently to find methods of cleaning soil of heavy metals, such as phytoremediation [9, 13, 17] for example. Plants manifesting high capabilities of accumulating heavy metals are also sought [6, 10, 11] to serve the same purpose. Ability to select species of plants which are either resistant to heavy metals, or can accumulate great amounts of them, would certainly facilitate reclamation of contaminated areas [14]. Many authors aimed at determining the species tolerant to heavy metals, which would maintain development and reproductivity at concentrations unbearable for others. Among species with higher tolerance to the presence of heavy metals in soil are *Sida hermaphrodita Rusby*, amaranth, Jerusalem artichoke and fibrous plants such as hemp or linseed [2, 7, 8, 9, 15].

The aim of our investigation was to analyse the influence of heavy metal pollution of soil, namely with Cd, Pb, Ni, Cu and Zn upon both the yield and the content of such elements in the studied plants.

MATERIAL AND METHODS

The studies conducted from 1997 to 1999 in a vegetation hall were performed as a pot experiment on ordinary silt with cation exchange capacity (CEC) of 81.1 cmol (+) · kg^{-1}, pH KCl=6.0 and organic C content of 9.5%, which served as soil. The following heavy metal contents determined in 65% solution of HNO_3 and 70% $HClO_4$ were found: 1.2 mg of cadmium, 54.3 mg of lead, 5.0 mg of nickel, 13.8 mg of copper and 226.6 mg of Zn per 1 kg of dry mass soil (d.m.). The experimental layout comprised 8 treatments, each in 4 replications; a control with no heavy metal added, and 7 treatments for which the dose of heavy metals was increasingly higher (see Table 1 for details). Heavy metals were applied as water solutions of the following salts: $3CdSO_4 \cdot 8H_2O$, $CuSO_4 \cdot 5H_2O$, $NiSO_4 \cdot 7H_2O$, $Pb(NO_3)_2$ and $ZnSO_4 \cdot 7H_2O$. All pots received the same basic fertilisation with 0.3 g N as NH_4NO_3; 0.08 g P in KH_2PO_4; 0.20 g K in KH_2PO_4+KCl and 0.05 g $MgSO_4 \cdot 7H_2O$ per 1 kg of soil d.m. One week before seeds were sown, heavy metals and fertilisers were mixed with soil. Jerusalem artichoke, maize, *Sida hermaphrodita Rusby*, amaranth and hemp were chosen as the indicator plants. Vegetation periods differed from one particular species to another and on average (calculated over 3 years) were equal to 127, 99, 153, 88 and 99 days for Jerusalem artichoke, maize, *Sida*, amaranth and hemp, respectively. During vegetation the plants were watered with redistilled water so that the soil moisture was maintained at 60% of maximum water capacity. Only the fully ripe plants were harvested. They were subsequently dried at 75^oC and then the yield for top parts was determined. Concentration of Cd, Pb, Ni, Cu and Zn were determined after dry incineration with flame technique in a Philips PU 9100 X atomic absorption spectrophotometer (ASA) [16].

Table 1. Experimental layout

Treatment	Dose of heavy metals mg · kg^{-1} d.m. soil				
	Cd	Cu	Ni	Pb	Zn
0	control				
I	5	20	15	30	50
II	10	40	30	60	100
III	20	80	60	120	200
IV	40	160	120	240	400
V	80	320	240	480	800
VI	160	640	480	960	1600
VII	320	1280	960	1920	3200

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RESULTS AND DISCUSSION

The obtained yields vary from species to species, but the level of heavy metal contamination of soil and the year the experiment was performed in, were the other dependable factors, as it is presented in Table 2.

Table 2. Plant yields (g d.m. · pot^{-1})

Treatment	Plant species								
	Jerusalem artichoke		Maize		*Sida herm.*	Amaranth		Hemp	
	Aerial	Roots	Aerial	Roots	Aerial	Aerial	Roots	Aerial	Roots
	1997								
0	112.4	19.9	203.3	27.3	118.0	155.3	17.5	199.1	9.5
I	108.3	19.7	210.0	27.4	123.9	157.9	17.3	197.2	9.5
II	105.9	19.2	194.5	19.5	111.9	155.8	17.4	152.5	8.7
III	89.9	16.4	176.4	17.6	115.4	136.5	15.6	135.8	8.8
IV	35.1	8.2	122.2	15.9	106.0	82.9	8.8	139.9	8.1
V	4.8	2.0	38.3	8.7	63.7	–	–	6.4	1.2
LSD$_{0.05}$	17.2	2.08	8.9	2.9	54.5	14.3	1.12	8.6	0.9
	1998								
0	323.1	41.2	223.4	31.3	590.2	173.0	18.3	167.3	12.6
I	340.0	41.9	224.1	29.7	593.9	169.1	17.5	168.5	11.0
II	323.4	41.0	196.7	24.7	577.2	171.7	17.3	148.5	9.4
III	283.9	25.2	158.6	24.5	572.8	134.3	16.2	151.2	9.9
IV	38.0	6.0	82.7	16.6	566.3	83.4	8.6	104.7	8.9
V	7.5	3.2	54.3	8.9	374.8	–	–	5.6	0.4
VI	–	–	–	–	231.8	–	–	–	–
VII	–	–	–	–	11.3	–	–	–	–
LSD$_{0.05}$	17.2	2.08	8.9	2.9	54.5	14.3	1.12	8.6	0.9
	1999								
0	331.4	39.9	216.7	31.5	855.2	172.7	18.0	169.1	12.5
I	337.3	41.1	216.8	32.0	883.6	171.4	17.6	166.0	12.2
II	324.1	38.7	193.1	23.0	837.7	172.5	17.7	146.2	10.9
III	275.7	23.3	164.8	20.7	852.3	140.0	15.8	144.9	9.7
IV	35.5	7.0	82.3	15.7	844.1	86.3	9.9	109.8	8.8
V	9.9	3.3	60.2	7.8	628.8	–	–	5.4	0.9
VI	–	–	–	–	414.3	–	–	–	–
VII	–	–	–	–	395.7	–	–	–	–
LSD$_{0.05}$	17.2	2.08	8.9	2.9	54.5	14.3	1.12	8.6	0.9

It was found that Jerusalem artichoke cannot be cultivated on soil which contamination per 1 kg of dry mass soil exceeds 80 mg of Cd, 480 mg of Pb, 240 mg of Ni, 320 mg of Cu, and 800 mg of Zn. The concentrations of heavy metals on treatments VI and VII proved to be too high and toxic for the plants. The influence of heavy metals on the yield of top parts, roots and tubers of Jerusalem artichoke was registered as toxic starting from the 3rd level of heavy metal contamination of soil. Decrease in the yields depended on both the year of the experiment and the cultivated treatment and ranged between 20 - 96% and 17-90% in 1997, 12-98% and 39-92% in 1998, 17-97% and 41-92% in 1999, for top parts and roots, respectively. Percentages calculated with reference to the control treatment. Similarly, a decline in tuber yield was also observed from the 3rd level of heavy metal contamination of soil and it depended both on the cultivated treatment and the year of the experiment. The respective percentage ranges were as follows: 26-91% in 1997; 36-97% in 1998, and 36-96% in 1999; all related to the control treatment.

The treatments VI and VII, where the highest levels of heavy metal contamination of soil were applied, namely 160 and 320 of cadmium, 640 and 1280 of copper, 480 and 960 of nickel, 960 and 1920 of lead, and finally 1600 and 3200 of zinc (all in mg per 1 kg of d.m. soil) for each treatment respectively, were found infeasible to cultivate maize on. Irrespective of the year of the experiment, a decline in top biomass for maize was registered already at the 2nd level of heavy metal contamination of soil. The observed decrease amounted to 6% in the first year, 12% in the second, and 11% in the third, while compared with the control in the respective years. Drops in maize top yields with increased doses of heavy metals (treatments III-V) were even more pronounced and ranged from 19% to 81%, from 29% to 76%, and from 24% to 72% in comparison with the control, for 1997, 1998, and 1999, respectively. The 2^{nd} level of heavy metal contamination of soil proved to be critical also for yielding of maize roots, as it was in case of maize top parts, and in comparison to the control amounted to the ranges between 29-68%, 21-72%, and 27-75% in the three consecutive years of the experiment.

In case of *Sida hermaphrodita Rusby*, which is a perennial, only the effect of heavy metals on the amount of top parts yield was studied. In the first year of the experiment (1997) the plants germinated neither at 6^{th} nor at 7^{th} levels of soil contamination with heavy metals. However, in the second year another attempt was made to cultivate *Sida hermaphrodita Rusby* on the treatments - this time by planting the root seedlings instead of sowing seeds, as it was in 1997. The data in Table 2 undoubtedly show that the plants adapted to such conditions. In the first year a considerable decline in *Sida* top parts yields was noticed for treatment V, and its top part yield reached 46% in relation to the control. In the second year of the experiment, the yields of tested plant still decreased at level V of soil contamination but amounted to 36% in relation to the control. Higher doses of heavy metals caused more rapid decrease in *Sida* yields, namely 61% on treatment VI and 98% on treatment VII, when compared to the same control. In the third year (1999) a significant decline in Sida top part yield, gaining approximately 26% in relation to the control treatment, was observed again at the 5^{th} level of contamination. Higher levels of contamination, applied on treatments V-VII, demonstrated milder drop than in 1998 and reached 52-54% in relation to the control one.

It was found for amaranth that soil contamination higher than 40 mg of cadmium, 240 mg of lead, 120 mg of nickel,160 mg of copper, and finally 400 mg of zinc per 1 kg of d.m. soil prevents its cultivation. The seeds of amaranth sown on treatment V, VI and VII with high heavy metal concentrations die-back immediately after germination. A decline in amaranth yield in the investigated period started at the 3^{rd} level of soil contamination. A significant decrease in top parts yield on treatment III reached, in relation to the control, 12%, 22%, and 19% in 1997, 1998 and 1999, respectively. On treatment IV a decrease in amaranth top parts yield was greater in 1997-1999 and reached respectively 47%, 52%, and 50% in comparison with the control. Diversification of heavy metal dose in soil affected also the amount of root yield. In the concerned period between 1997 and 1999, again the 3^{rd} level of soil contamination with heavy metals produced a noticeable decline in amaranth root yield. The decrease, related to the control, reached 11%, 11%, and 12% in the three consecutive years of the experiment. For 4^{th} level of soil contamination the decrease in root yield, respectively, amounted to 50%, 53%, and 45%.

A high level of soil contamination with heavy metals on treatments VI and VII caused hemp seeds to die-back immediately after germination. Heavy metal toxic effect on hemp yield became apparent already at the 2^{nd} level of soil contamination. In comparison with the control, the decline in top parts yield on treatments II-V in the concerned period, reached 9%-96%, 11%-97%, and 14%-97% in the three consecutive years. Increased doses of heavy metals also influenced diversification of root dry matter yields. The second level of soil contamination with heavy metals, i.e. 10 mg of cadmium, 60 mg of lead, 30 mg of nickel, 40 mg of copper, and 100 mg of zinc per 1 kg of dry mass soil, proved also to be the threshold for a significant decline in root yield. In relation to the control, the decrease in hemp root yield on objects II-V fell into ranges 11-87%, 25-91%, and 13-93% in the consecutive years.

The influence of heavy metals in soil upon the quantity of plant yield analysed in the paper was found to be highly diversified. Such inter-species differences in the amount of yields were also registered in some earlier works [1, 5]. A negative influence of high concentrations of heavy metals on the growth, development and yielding of plants is a well known phenomenon [10, 11, 12]. Studies conducted by other authors suggested that plants can cumulate considerable amounts of heavy metal elements from the soil, provided that their concentration in soil is high enough. Nevertheless, the effect is not beneficial since at the same time a rapid decrease of biomass occurs [2, 7, 8, 9].

Figures 1-10 reveal that a raise in concentration of heavy metals in soil was accompanied by their increased concentrations in the plants. Relatively great differences of heavy metal contents in the tested species were easy to observe already between the control treatment and particular levels of soil contamination. Most likely, it results from the revealed tendency of species manifesting great capacity for accumulating heavy metal elements.

Fig. 1. Concentration of Cd in aerial (mean, 1997-99)

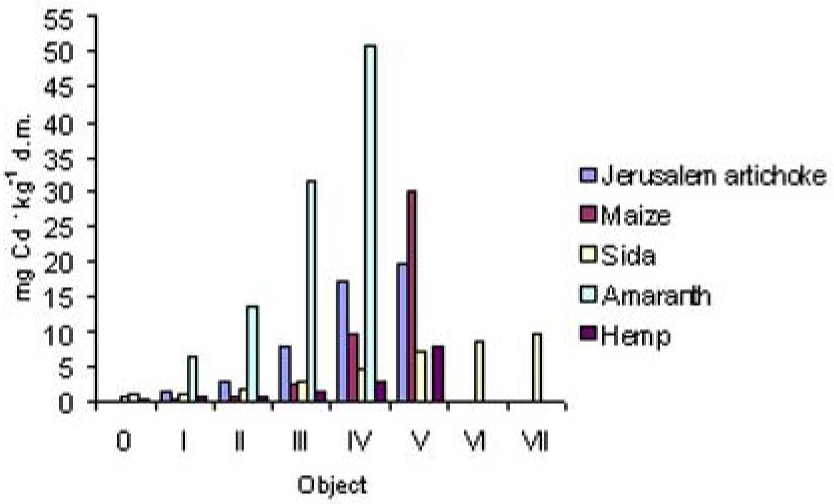

Fig. 2. Concentration of Pb in aerial (mean, 1997-99)

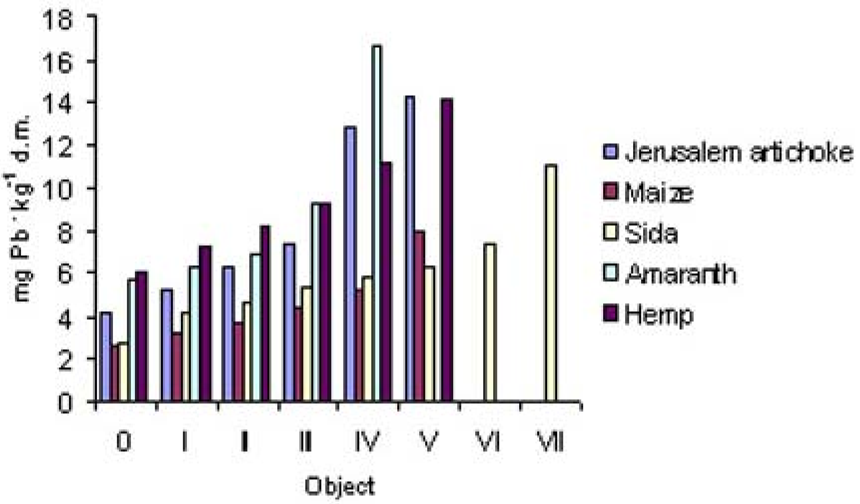

Fig. 3. Concentration of Ni in aerial (mean, 1997-99)

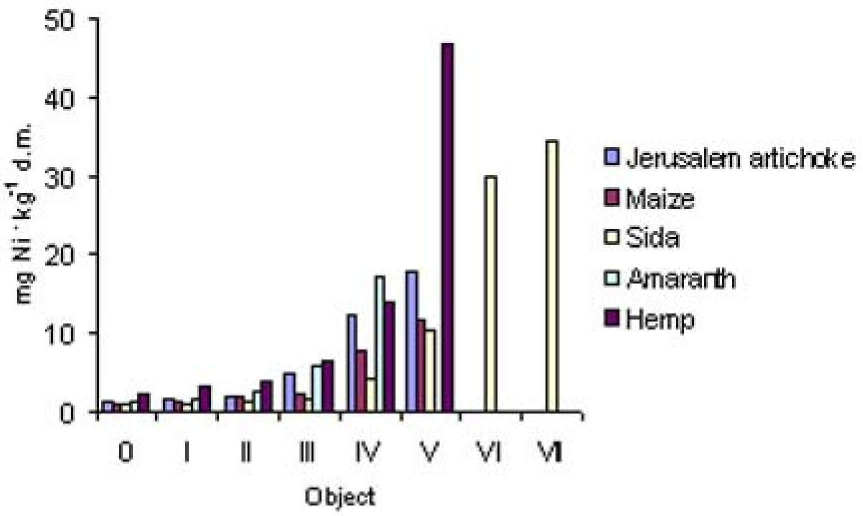

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Fig. 4. Concentration of Cu in aerial (mean, 1997-99)

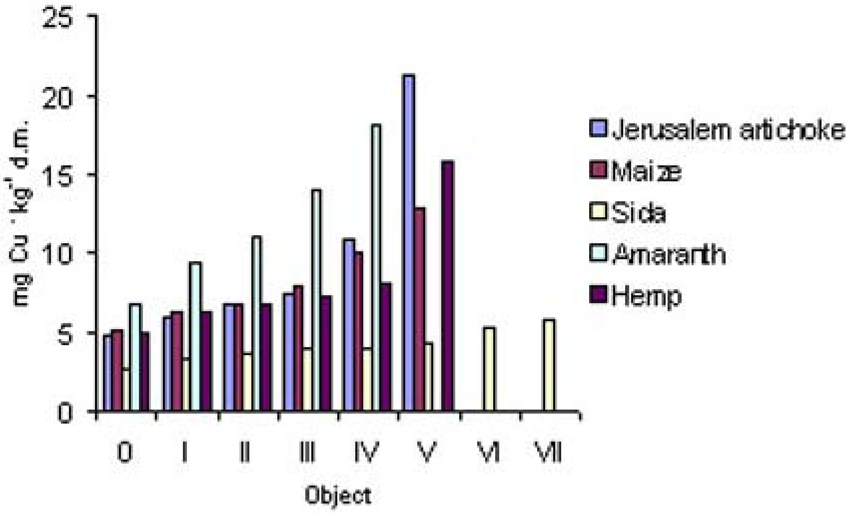

Fig. 5. Concentration of Zn in aerial (mean, 1997-99)

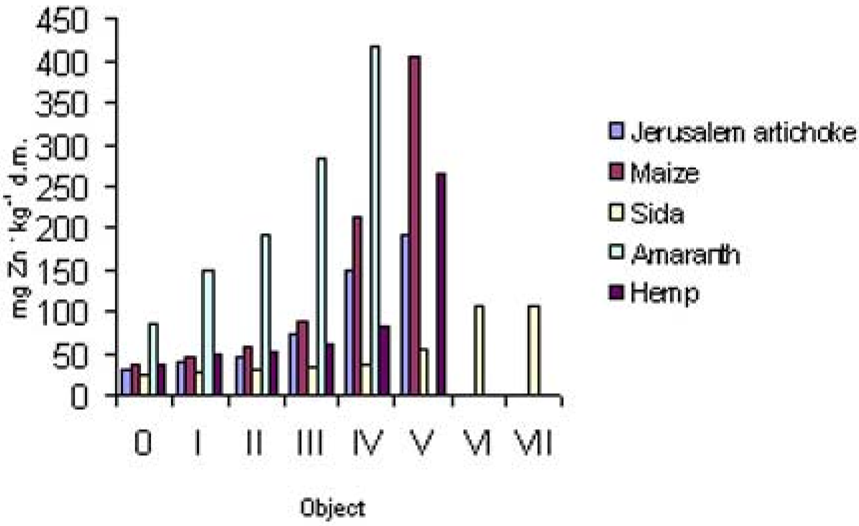

Fig. 6. Concentration of Cd in roots (mean, 1997-99)

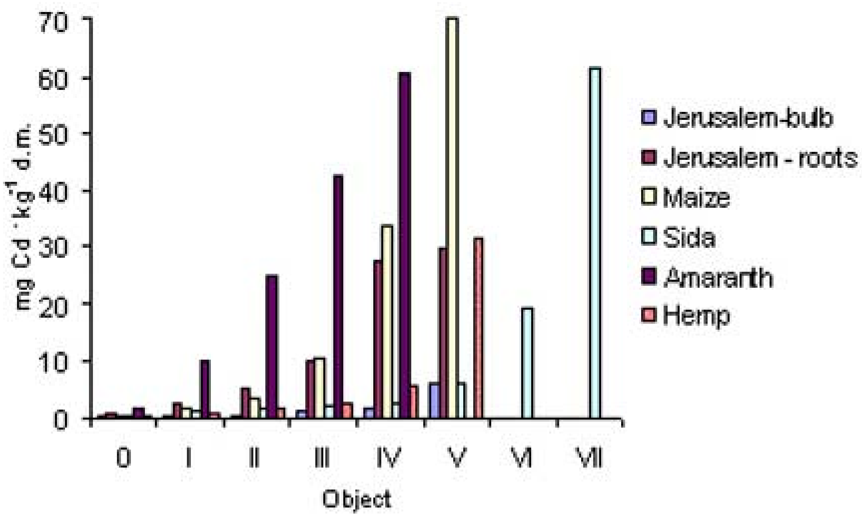

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Fig. 7. Concentration of Pb in roots (mean, 1997-99)

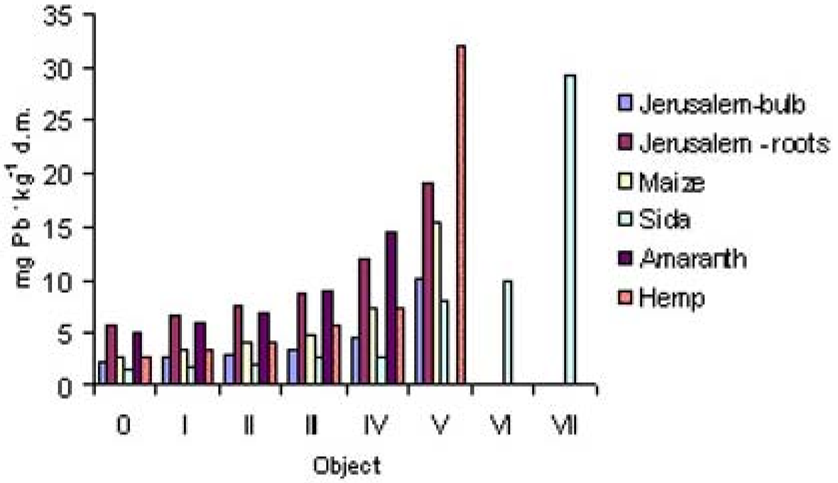

Fig. 8. Concentration of Ni in roots (mean, 1997-99)

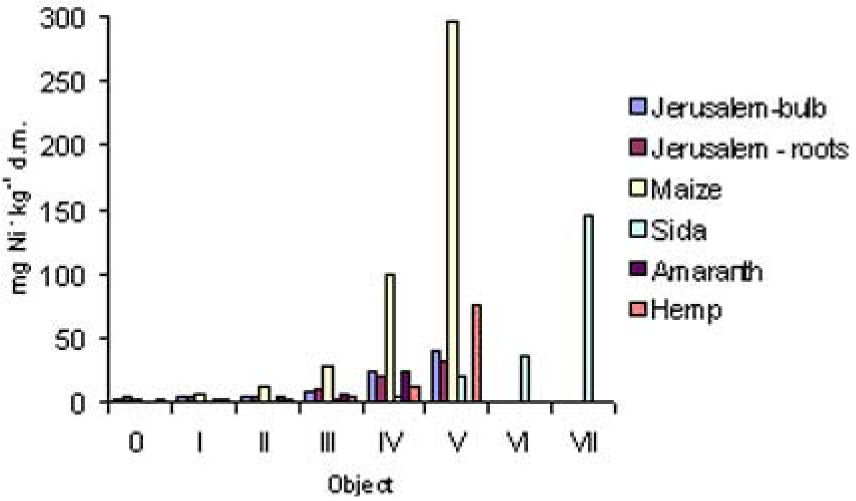

Fig. 9. Concentration of Cu in roots (mean, 1997-99)

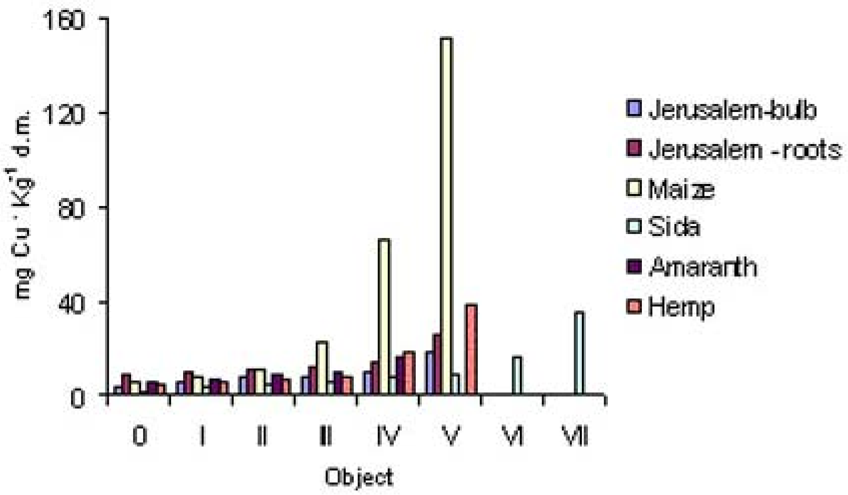

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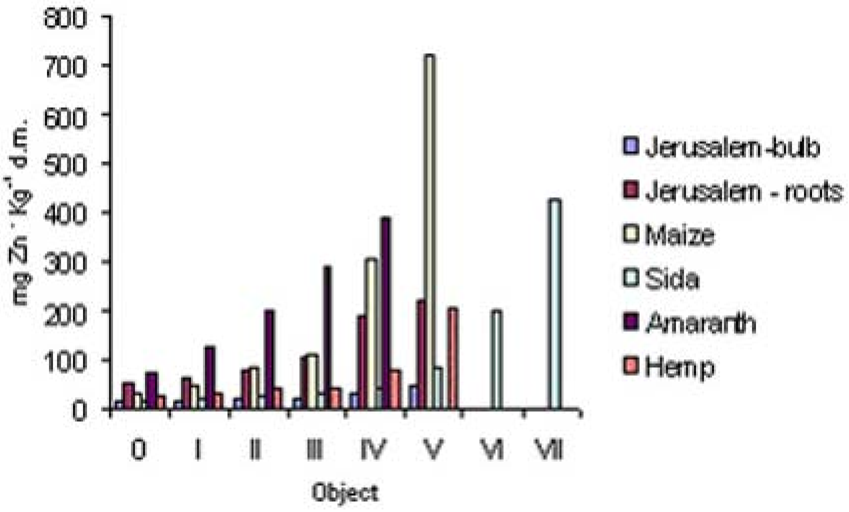
Fig. 10. Concentration of Zn in roots (mean, 1997-99)



For particular plants heavy metal contents, in mg per 1 kg of dry mass soil, depending on the analysed treatment and part of the plant, ranged within the following limits:

- in Jerusalem artichoke: 0.19-29.84 Cd, 2.17-19.12 Pb, 1.58-40.59 Ni, 4.11-25.90 Cu, 15.93-222.12 Zn;
- in maize: 0.22-70.08 Cd; 2.64-15.35 Pb; 1.16-296.65 Ni; 5.09-151.30 Cu, 33.60-724.39 Zn;
- in *Sida hermaphrodita Rusby*: 0.57-61.75 Cd; 1.48-29.22 Pb; 0.44-145.70 Ni; 2.30-35.27 Cu, and 18.98-426.33 Zn;
- in amaranth: 1.20-60.41 Cd; 4.98-16.56 Pb; 1.10-24.87 Ni; 5.64-18.16 Cu, and 73.96-417.59 Zn;
- in hemp: 0.32-31.48 Cd; 2.69-32.13 Pb; 1.99-76.52 Ni; 4.90-38.09 Cu, and 19-267.33 Zn

With regard to heavy metal contents in the top parts, the plants may be ranked from the highest to the lowest values, in the following order:

- cadmium: amaranth, maize, Jerusalem artichoke, Sida hermaphrodita Rusby, and hemp;
- lead: amaranth, Jerusalem artichoke, hemp, *Sida hermaphrodita Rusby* and maize;
- nickel: hemp, *Sida hermaphrodita Rusby*, Jerusalem artichoke, amaranth and maize;
- copper: Jerusalem artichoke, amaranth, hemp, maize and *Sida hermaphrodita Rusby*;
- zinc: amaranth, maize, hemp, Jerusalem artichoke and *Sida hermaphrodita Rusby*.

Concentrations of heavy metals in the roots of concerned plants were more diversified than in their top parts. The ranking of plants, from the highest to lowest concentrations of heavy elements looks as follows:

- cadmium: maize, Sida hermaphrodita Rusby, amaranth, hemp and Jerusalem artichoke;
- lead: hemp, *Sida hermaphrodita Rusby*, Jerusalem artichoke, maize and amaranth;
- nickel: maize, *Sida hermaphrodita Rusby*, hemp, Jerusalem artichoke and amaranth;
- copper: maize, hemp, *Sida hermaphrodita Rusby*, Jerusalem artichoke and amaranth;
- zinc: maize, Sida hermaphrodita Rusby, Jerusalem artichoke and hemp.

The plants are characterised by an individual, species dependent, ability to uptake heavy metals and different tolerance to their high concentrations [12, 19]. Different specific plant resistance to heavy metal contents in soil was also observed in the studies of Galler [4] and Gambuś [6]. Inhibitory influence of heavy metals on growth and development of plant top parts and roots is also very important for reclamation and phytoremediation processes in chemically degraded areas [2, 3].

The results confirmed the earlier data on the element contents being diversified by both the species and analysed parts of plants. The analysis of the data led the authors to the conclusion that the higher is heavy metal concentration in soil, the higher is the content of heavy metal elements in the plants. Relatively big differences in heavy metal contents were detected in plant species cultivated on the unpolluted treatments and at various levels of soil contamination.

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CONCLUSIONS

Results obtained from the conducted pot experiments allow to draw the following conclusions:

1. High diversification in plant yielding which depends on the level of soil contamination with heavy metals was found. A significant decline in the plant yield occurred at the 2nd, 3rd or 5th level of soil contamination with heavy metals for maize and hemp, Jerusalem artichoke and amaranth, and *Sida hermaphrodita Rusby*, respectively.
2. Great differentiation in the contents of the concerned heavy metals was observed. It depends mainly on the plant species. However, the contents in the examined species revealed also a dependence on the level of soil contamination and it increased with higher heavy metal concentrations in soil.
3. Accumulation of heavy metals in the top parts, for the highest tolerable level of heavy metal contamination of soil, increased in the following order:

   – cadmium: hemp, *Sida hermaphrodita Rusby*, Jerusalem artichoke, maize and maranth;
   – lead: maize, *Sida hermaphrodita Rusby*, hemp, Jerusalem artichoke and amaranth;
   – nickel: maize, amaranth, Jerualem artichoke, *Sida hermaphrodita Rusby* and hemp;
   – copper: *Sida hermaphrodita Rusby*, maize, hemp, amaranth and Jerusalem artichoke;
   – zinc: *Sida hermaphrodita Rusby*, Jerusalem artichoke, hemp, maize and amaranth

4. Accumulation of heavy metals in the roots, for the highest tolerable level of heavy metal contamination of soil, increases in the following order:

   – cadmium: Jerusalem artichoke, hemp, amaranth, *Sida hermaphrodita Rusby*s and aize
   – lead: amaranth, maize, Jerusalem artichoke, *Sida hermaphrodita Rusby* and hemp
   – nickel: amaranthus, Jerusalem artichoke, hemp, *Sida hermaphrodita Rusby* and maize
   – copper: amaranthus, Jerusalem artichoke, *Sida hermaphrodita Rusby*, hemp and maize
   – zinc: hemp, Jerusalem artichoke, amaranth, *Sida hermaphrodita Rusby* and maize

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